

Minimal Z' models and the 125 GeV Higgs boson

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Abstract

The 1-loop renormalization group equations for the minimal Z' models encompassing a type-I seesaw mechanism are studied in the light of the 125 GeV Higgs boson discovery. This model is taken as a benchmark for the general case of singlet extensions of the standard model. The most important result is that negative scalar mixing angles are favoured with respect to positive values. Further, a minimum value for the latter exists, as well as a maximum value for the masses of the heavy neutrinos, depending on the vacuum expectation value of the singlet scalar.

Keywords: Z' , seesaw, singlet scalar, 125 GeV Higgs boson.

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1. Introduction

Both the ATLAS and CMS collaborations have reported the discovery of a resonance with a mass of around 125 GeV, immediately associated with the long-sought after Higgs boson [1]. With this discovery, the standard model (SM) of particle physics is considered as complete. However, such low mass is incompatible with the stability of the SM up to the Plank scale (M_{Pl}), as newly confirmed by a 2-loop analysis of the scalar potential [2] (see, however, [3, 4]).

It is also known that simple extensions of the SM can ameliorate this behaviour. It is sufficient to enlarge the scalar sector by means of a singlet scalar field to restore the validity of the SM up to very large scales (see, e.g., [5, 6] and references therein). Nonetheless, other problems are still unsolved,

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for instance the pattern of masses and mixing angles of the neutrinos and the presence of dark matter to just mention a few. More involved extensions of the SM are therefore needed.

A very simple and yet interesting SM extension is the so-called “minimal Z' models”, in which the SM gauge group is enlarged by a $U(1)_{B-L}$ gauged symmetry [7]. The vanishing of chiral anomalies requires to minimally include 3 right-handed (RH) neutrinos, while the extra $U(1)$ symmetry is spontaneously broken by a new complex singlet scalar field, responsible to give mass to the related Z' boson. While the scalar and gauge sectors are unambiguous, various realizations exist for the fermion content of the model, that can encompass a gauged type-I seesaw mechanism in its minimal version [8, 9], or the more involved inverse seesaw mechanism if new lepton pairs are included, thereby providing a solution for neutrino masses, dark matter and baryon asymmetry at once [10]. Higher fermion representations can be invoked to explain the apparent enhancement in the Higgs-to-diphoton signal as recently observed, if one consider negative values for the scalar mixing angle, compatible with LEP and LHC observations, as in Ref. [11].

It is a fact that the evolution of the scalar parameters in simple SM extensions does depend only very marginally on the gauge sector and sensibly on the fermions only if the latter are very heavy. This has explicitly been noted in Ref. [6], although the latter reference does not study in details its consequences. Further, in Ref. [9] a renormalization group (RG) study of the minimal Z' models has been performed when the SM-like Higgs mass was not known. Stimulated by these arguments, in this letter we study the constraints that the 125 GeV SM-like Higgs boson imposes on the minimal Z' models via the 1-loop RG running in the latter, taken as a benchmark for minimal scalar extensions of the SM. Imposing stability up to the Plank scale, we are able to determine predictions for the mass of the heavy scalar field and constraints on the scalar mixing angle. In a model-dependent analysis, we will show the existence of a minimum value for the latter and of an upper value for the mass of the heavy neutrinos, when considering just the minimal case of the type-I seesaw mechanism. For a similar analysis in the SM with RH neutrinos and an effective type-I seesaw mechanism, see [4]. We will discuss how all these statements depend upon the $U(1)_{B-L}$ -breaking scalar vacuum expectation value (vev).

2. The minimal Z' models

We describe here the minimal Z' models. Following the notation of Ref. [9], the SM gauge group is extended by a gauged $U(1)_{B-L}$ symmetry and a new complex scalar field χ is required to provide mass to the further gauge boson.

In a suitable basis with diagonal kinetic terms, the gauge covariant derivative for the neutral sector reads

$$D_\mu \equiv \partial_\mu + \cdots + ig_1 Y B_\mu + i(\tilde{g}Y + g'_1 Y_{B-L})B'_\mu. \quad (1)$$

The scalar potential is given by

$$V(H, \chi) = m^2 H^\dagger H + \mu^2 |\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^\dagger H |\chi|^2, \quad (2)$$

where H and χ are the complex scalar Higgs doublet and singlet fields with $B-L$ charges 0 and +2, respectively. In unitary gauge, we assume $\langle H \rangle \equiv \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ and $\langle \chi \rangle \equiv \frac{x}{\sqrt{2}}$ with v and x real and non-negative. We denote by h_1 and h_2 the scalar fields of definite masses, m_{h_1} and m_{h_2} respectively, and we conventionally choose $m_{h_1}^2 < m_{h_2}^2$. Further, we call α the mixing angle between the real scalar states, with $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$. For our numerical study, it is useful to rewrite the parameters in the Lagrangian in terms of the physical quantities m_{h_1} , m_{h_2} and $\sin 2\alpha$ after inversion:

$$\begin{aligned} \lambda_1 &= \frac{m_{h_1}^2}{4v^2}(1 + \cos 2\alpha) + \frac{m_{h_2}^2}{4v^2}(1 - \cos 2\alpha), \\ \lambda_2 &= \frac{m_{h_2}^2}{4x^2}(1 + \cos 2\alpha) + \frac{m_{h_1}^2}{4x^2}(1 - \cos 2\alpha), \\ \lambda_3 &= \sin 2\alpha \left(\frac{m_{h_2}^2 - m_{h_1}^2}{2xv} \right). \end{aligned} \quad (3)$$

Generally, a bound on x is set by LEP measurements. In the type-I seesaw case here discussed, $x > 3.5$ TeV [9]. The LHC data are interpreted by identifying h_1 with the recently observed boson, i.e., $m_{h_1} = (125 \pm 1)$ GeV, and by restricting $|\sin \alpha| \leq 0.3$. For such small scalar mixing angles, $\cos^2 \alpha \sim 1$, hence

$$\lambda_1 - \lambda_1^{SM} \equiv \Delta\lambda_1 \simeq \frac{(m_{h_2} \sin \alpha)^2}{2v^2} \quad (4)$$

with $\lambda^{SM} = m_h^{SM}/(2v^2)$ is the SM value.

We have so far described the sectors that all the various realisations of the minimal Z' models have in common. As a representative for the fermion sector, we consider here the type-I seesaw mechanism, that requires to introduce 1 RH neutrino per generation (ν_R) to ensure the vanishing of the chiral anomalies. The new Yukawa interactions are

$$\mathcal{L}_Y^\nu = -y_{jk}^\nu \overline{l_{jL}} \nu_{kR} \tilde{H} - y_{jk}^M \overline{(\nu_R)_j^c} \nu_{kR} \chi + \text{h.c.}, \quad (5)$$

where $\tilde{H} = i\sigma^2 H^*$ and i, j, k take the values 1 to 3, where the last term is the Majorana contribution and the first term the usual Dirac one. These are the only allowed gauge invariant terms, provided that $Y_{B-L}^X = 2$. Neutrino mass eigenstates, obtained after applying the seesaw mechanism, will be called ν_l (with l standing for light) and ν_h (with h standing for heavy), where the first ones are the SM-like ones.

The complete set of RGEs for the generic model are derived for the parameters in the Lagrangian and can be found in Ref. [9]. We show here only those pertaining the scalar quartic couplings, subject of this letter:

$$\beta_1 \equiv \frac{d\lambda_1}{dt} = \frac{1}{16\pi^2} (24\lambda_1^2 + \lambda_3^2 - 6y_t^4 + 12\lambda_1 y_t^2), \quad (6)$$

$$\beta_2 \equiv \frac{d\lambda_2}{dt} = \frac{1}{8\pi^2} \left(10\lambda_2^2 + \lambda_3^2 - \frac{1}{2} \text{Tr} [(y^M)^4] + 4\lambda_2 \text{Tr} [(y^M)^2] \right), \quad (7)$$

$$\beta_3 \equiv \frac{d\lambda_3}{dt} = \frac{\lambda_3}{8\pi^2} (6\lambda_1 + 4\lambda_2 + 2\lambda_3 + 3y_t^2 + 2\text{Tr} [(y^M)^2]), \quad (8)$$

with $t = \ln Q$. Notice that sub-leading gauge coupling terms are not shown because being irrelevant for the discussion, but have been taken into account in the derivation of the results. These equations match those in Ref. [6], and make explicit the model-dependent contribution arising from the fermionic sector. When the neutrinos are relatively light and their Yukawa couplings small (meaning that their contribution can be neglected), our results can be interpreted as general for the class of singlet-extended SM theories. (For similar analyses of the SM with singlet extensions, see [12] and references therein.)

For their numerical study, we proceed as in [9], putting boundary conditions at the electroweak (EW) scale on the free physical observables: m_{h_2} , α , x , $M_{\nu_h}^{1,2,3}$, that we trade for λ_1 , λ_2 , λ_3 , $y_{1,2,3}^M$. The impact of the variation of the Higgs and top masses within 1σ is also considered, being $m_{h_1} = (125 \pm 1)$

GeV and $m_{top} = (173.1 \pm 0.7)$ GeV, respectively. Finally, gauge parameters are sub-leading in our considerations and need not be specified. For completeness, we used the same values as in [9]. The free parameters in our study are then m_{h_2} (the heavy Higgs mass), α (the scalar mixing angle), x (the $B - L$ -breaking vev) and m_{ν_h} (the heavy neutrino mass when taking neutrinos as mass degenerate). The general philosophy is to fix in turn some of the free parameters and scan over the other ones, individuating the allowed regions fulfilling the following set of conditions:

$$0 < \lambda_{1,2,|3|}(Q') < 1 \quad \forall Q' \leq Q, \quad (9)$$

(usually referred to as the “triviality” condition. Notice that $\lambda_{|3|} \equiv |\lambda_3|$) and

$$0 < \lambda_{1,2}(Q') \quad \text{and} \quad 4\lambda_1(Q')\lambda_2(Q') - \lambda_3^2(Q') > 0 \quad \forall Q' \leq Q, \quad (10)$$

(usually referred to as the “vacuum stability” condition, i.e., the vacuum of the theory must be well-defined at any scale $Q' \leq Q$). In these equations, we have defined a parameter to be “perturbative” for values less than unity. As described in Ref. [9], this is a conservative definition. Regarding eq. (10) and in particular its second term, notice that, in contrast to the SM in which it is sufficient the Higgs self-coupling λ be positive, in this model said condition can be violated even for positive $\lambda_{1,2,3}$.

3. Numerical Results

To understand the following results, some considerations on the RGEs are in place. First, the reason why extending the SM by a singlet scalar is sufficient to stabilize the RG evolution of the scalar quartic couplings is explicitly shown in eq. (4). Through the scalar mixing, larger values for the SM-like quartic coupling λ_1 are needed to recover the same physical mass. Conversely, the heavy Higgs boson h_2 contributes additively to the EW boundary condition of λ_1 , proportionally to the scalar mixing angle. This means that to obtain the same “uplifting” of the coupling to the stability region, larger h_2 masses are needed when considering smaller mixing angles α (per fixed vev x). Second, for a fix value of x , m_{h_2} cannot grow indefinitely to compensate for smaller and smaller values of α , being limited by the occurrence of a Landau pole for λ_2 . Third, positive and negative values for α (and similarly for λ_3 in our conventions) are not symmetric, as clear from eq. (8). In fact, the running of λ_3 via said equation depends on the

relative sign between $(\lambda_1 + \lambda_2)$ and λ_3 . Given that $\lambda_1, \lambda_2 > 0$, there will be constructive\destructive interference when α assumes positive\negative values. This means that the evolution of $\lambda_3(Q)$ is more stable for negative angles, that hence appear to be favoured with respect to positive angles. Interestingly, negative values are physically preferred in some cases if one tries to explain the enhancement in the diphoton signal of the SM-like Higgs boson [11]. Last, heavy neutrinos can play a role in destabilising the evolution of λ_2 , as the top-quark for the SM quartic coupling, if heavy enough (see eq. (7)). The request of stability of the model up to a certain scale then imposes an upper bound on the RH neutrino Yukawa couplings and therefore on the heavy neutrino masses (per fixed vev). Unless otherwise specified, we will consider $M_{\nu_h} = 200$ GeV throughout this letter.

Figure 1 shows most of these features at once, for $x = 7.5$ TeV. There exist values for m_{h_2} that are stable up to the Plank scale for negative scalar mixing angles for all the considered top-quark masses, but the similar case for positive values exist only for $m_{top} < 172.8$ GeV (i.e., for the central value of m_{top} , the model is not stable up to Plank scale for positive scalar mixing angle when the vev x is small, see figure 3). Further, it shows that if the RH-neutrino Yukawa couplings are large, the model can be stable only up to scales smaller than M_{Pl} , again with negative scalar mixing angles being stable for larger scales than the $\alpha > 0$ case. We get that for $\sin \alpha = -0.3$, $400 < m_{h_2}/\text{GeV} < 430$ (see figure 4), with eq. (4) telling that the allowed heavy Higgs mass scales with $\sin \alpha$ per fixed vev (i.e., for $\sin \alpha = 0.1$, $m_{h_2} \simeq 1.2$ TeV is stable up to M_{Pl}).

The scaling of m_{h_2} with $\sin \alpha$ is displayed in figures 2–3, for negative and positive angles, respectively. It is clear here that for small x values, negative angles are favoured over positive values. In fact, one needs very large vev values $\mathcal{O}(100)$ TeV for m_{h_2} – $\sin \alpha$ combinations stable up to M_{Pl} to exist, for positive angles smaller than 0.1 rads. For negative angles, there exist heavy Higgs masses stable up to the Plank scale for $\sin \alpha \lesssim -0.025(-0.01)$ for $x = 7.5(15)$ TeV. The substantial difference comes from the evolution of λ_3 , that runs less when negative, such that the violation of vacuum stability is pushed to higher scales. For positive angles, it occurs instead much earlier, and larger vevs (per fixed m_{h_2}) are required to keep eq. (10) satisfied. Depending on the $B - L$ -breaking vev x , figures 2–3 show that a minimum scalar mixing angle exist (in absolute value), roughly equal to $-0.023(-0.011)$ rads for $x = 7.5(15)$ TeV. In the positive domain, for $x = 75$ TeV one needs $\sin \alpha \geq 0.17$. For positive angles, a $\mathcal{O}(10\%)$ precision in the measurement of the Higgs

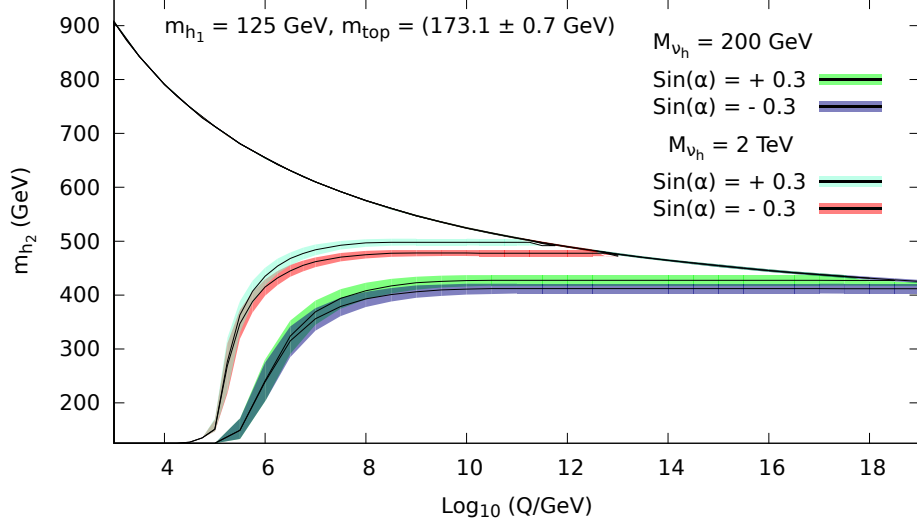


Figure 1: Allowed EW-scale heavy Higgs (h_2) masses as a function of the validity scale Q for $\sin \alpha = \pm 0.3$. Line thickness reflects a 1σ variation of the top-quark mass. Here, $x = 7.5$ TeV. (Allowed masses are in the area inside the black lines).

cross sections is hence sufficient to test this model for $x < \mathcal{O}(100)$ TeV. It is expected to reach this precision at the LHC, that therefore can easily confirm/exclude this region of the parameter space. Larger vevs and/or negative α values (that allow for much smaller minimum angles) require higher precision and therefore can be tested only at future linear colliders.

Regarding the allowed heavy Higgs masses, they do not depend substantially on the vev x , because the condition that is restricting the parameter space is given by the triviality bound on λ_1 , on which m_{h_2} impinges via eq. (4), independent from x . However, the existence of a minimum scalar angle and its value depend on x . As remarked, one cannot grow m_{h_2} indefinitely to compensate for smaller $\sin \alpha$ due to the appearance of a Landau pole for $\lambda_2(Q_{EW}) \sim \frac{m_{h_2}^2}{2x^2}$. Interestingly, when considering negative angles, violations of vacuum stability appear earlier than the Landau pole for λ_2 when increasing the $B - L$ -breaking vev x to very large values (bigger than $\mathcal{O}(50)$ TeV), opposite to the previous observation. This is because $\lambda_3(Q_{EW}) \sim \sin 2\alpha \frac{m_{h_2}^2}{x}$ (see eq. (3)), i.e., the boundary condition on λ_2 gets smaller than the one on

λ_3 for increasing values of x , causing violation of the vacuum stability earlier in the running.

Figure 4 shows that an upper limit on the heavy neutrino mass also exist for fixed x and $\sin \alpha$ values, depending on the scale of validity of the model. This was clear already from figure 1 and from the behaviour of the top-quark in the SM. In the case of the type-I seesaw mechanism under discussion, heavy neutrinos cannot be heavier than about 1.5(1.0) TeV when imposing stability up to the Plank scale, for $\sin \alpha = -0.3(+0.3)$. When $\sin \alpha = -0.1(-0.05)$, $M_{\nu_h} \lesssim 2(4)$ TeV. These values are for $x = 7.5$ and scale naively with it. The plot shows also a strong sensitivity from the actual top-quark mass, and it reinforces the observation that positive scalar mixing angles are stable up to the Plank scale for small x values only for top-masses lighter than its actual central value.

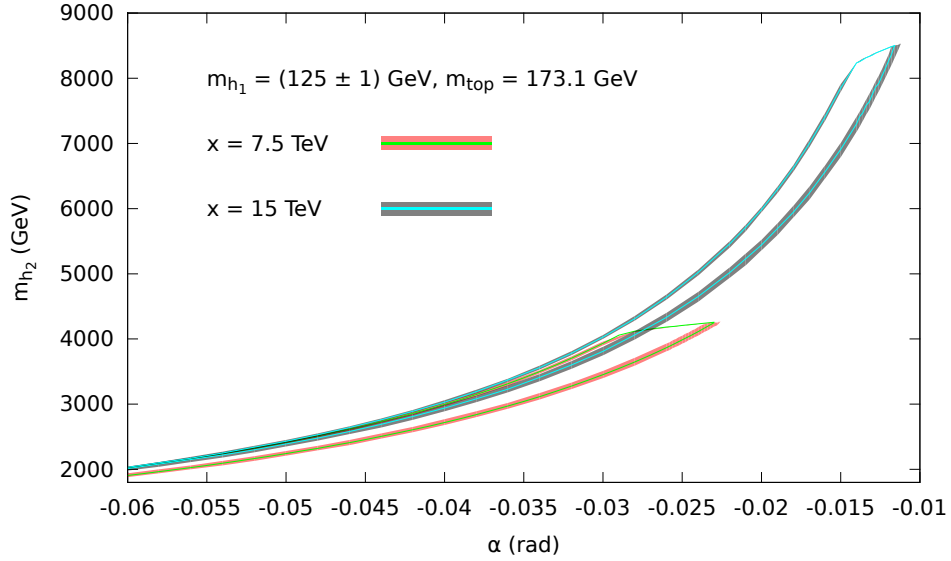


Figure 2: Allowed heavy Higgs mass as a function of the scalar mixing angle for *negative* values only. Thickness of the lines represent a 1σ variation on the SM-like Higgs mass. Here, $Q = 10^{19}$ GeV. (Allowed masses are in the area inside the lines).

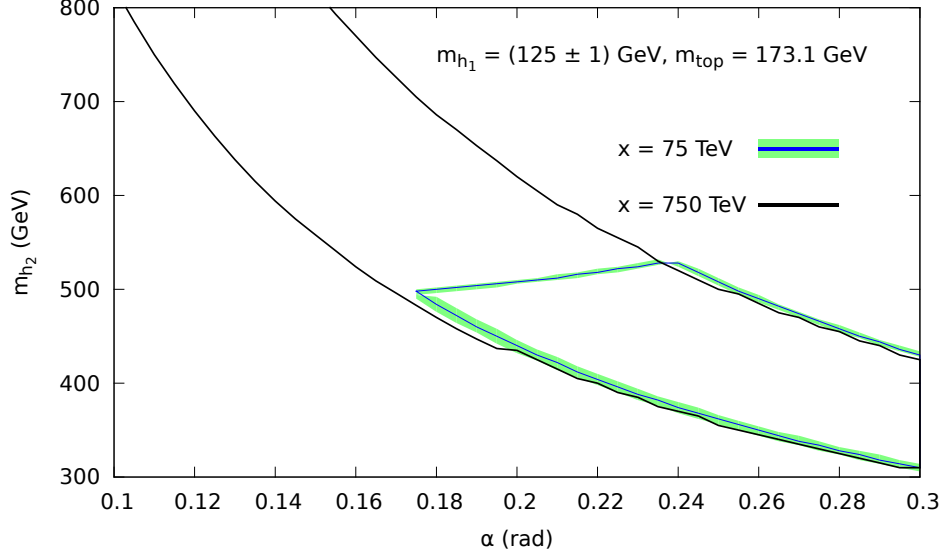


Figure 3: Allowed heavy Higgs mass as a function of the scalar mixing angle for *positive* values only. Thickness of the lines represent a 1σ variation on the SM-like Higgs mass. Here, $Q = 10^{19}$ GeV. (Allowed masses are in the area inside the lines).

4. Conclusions

It is well established that the presence of an extra scalar allows for the so-enlarged SM to be valid up to the Plank scale. In this letter we showed the case for the minimal Z' models, taken as representative for this type of minimal SM extensions. It was shown in Ref. [11] that negative scalar mixing angles can be employed to explain the SM-like Higgs-to-diphoton signal. The primary result of this work is that they are also favoured for small values of the $B - L$ -breaking vev with respect to positive values when stability up to the Plank scale is requested. It was also shown that a minimum value exist for the (absolute value of the) scalar mixing angle as well as a maximum value for the heavy neutrino mass, per fixed $B - L$ -breaking vev values, and how they depend on the latter.

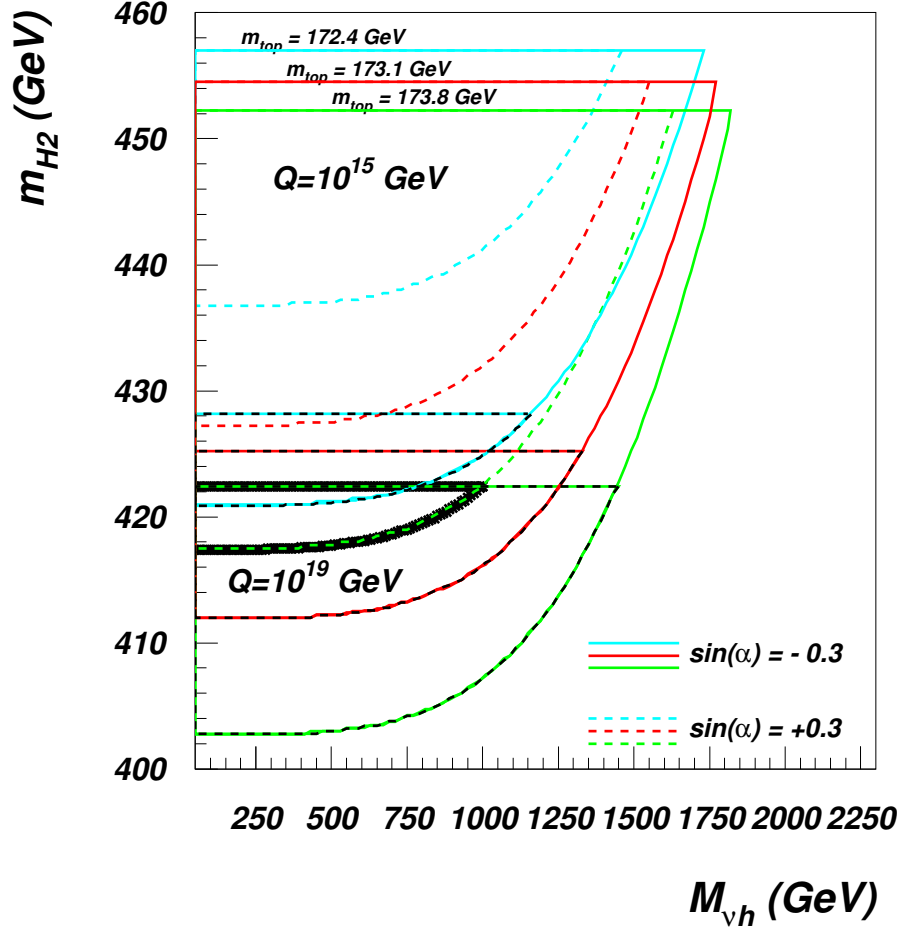


Figure 4: Allowed heavy Higgs masses as a function of the heavy neutrino masses. Color lines for $Q = 10^{15}$ GeV, dashed-coloured-on-black lines for $Q = 10^{19}$ GeV; solid and dashed coloured-black lines are for $\sin \alpha = -0.3$, dashed-coloured and dashed-coloured-on-thick-black lines are for $\sin \alpha = 0.3$. Here, $m_{h_1} = 125$ GeV, $x = 7.5$ TeV, and $\sin \alpha = 0.3$. (Allowed masses are in the area inside the lines).

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